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Procedia Engineering 106 (2015) 53 – 61

Procedia Engineering

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Dynamics and Vibroacoustics of Machines (DVM2014)

Development of Mathematical Model and Analysis of Characteristics of Gas Dampener for Power Plant Fuel Main Line

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Abstract

Providing stability and dynamic quality of fuel systems is very important problem when developing and during operation of power plants in many applications. For example, it is critical issue for longitudinal stabilization of launch vehicles (pogo attenuation). One of effective ways to provide rocket longitudinal stability is installation of a pogo suppression device (PSD) in the feed line. The paper presents a mathematical model of the gas PSD, its transient and frequency responses that can be used for the fuel system design. For developing mathematical model of the PSD, analytical methods and numerical simulation were applied, the software packages MatLab/Simulink and AMESim being used. The PSD input acoustic admittance was calculated. The developed model of the gas PSD can be used in the mathematical model of the fuel line when solving problem of longitudinal stability of launch vehicles and other issues of power plants design.

Peer-review under responsibility of organizing committee of the Dynamics and Vibroacoustics of Machines (DVM2014)

Keywords: gas dampener, dynamic characteristics, frequency characteristics, Simulink, AMESim

1. Introduction

One of traditional ways to ensure the dynamic characteristics of the power plant (PP) fuel system is to correct its frequency responses with the use of damping devices. When providing longitudinal stability of the launch vehicles it is necessary to keep different the resonant frequency of its shell and fuel lines, introducing damping of fuel flow oscillations [1, 2]. The solution to this problem cannot be performed only by choice of the design parameters of the fuel lines due to the nature of PP. Therefore there is a need to develop a means for correcting frequency responses of the fuel lines, so called the pogo suppression device (PSD). Despite the development of design solutions while

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Peer-review under responsibility of organizing committee of the Dynamics and Vibroacoustics of Machines (DVM2014)
doi:10.1016/j.proeng.2015.06.008

ensuring the sustainability of the PP together with fuel system, in the literature, little attention is paid to methods of calculation of corrective devices and their dynamic characteristics analysis. Among modern works devoted to the study of corrective devices may be noted [3], which describes a simplified analytical model and key parameters determined on the basis of experimental studies. The purpose of scientific research of the authors was to develop methods of calculating the frequency and transient characteristics of the PSD with a large orifice that is connected to the fuel line, the study of the influence of the design parameters of the damper on its dynamic characteristics. The main attention is paid to the definition of the input acoustic conductivity of the damper, as the main characteristic determining its effectiveness in ensuring the sustainability of the systems.

2. Development of the gas PSD mathematical model

In deriving the equation of PSD (Fig. 1) a number of simplifying assumptions are accepted: the working medium in the gas volume is an ideal gas; the needle pressure difference (at section 1-1) is supercritical; the sending-end impedance of diverting attached system equals zero; the heat exchange with the environment through the walls of GD is absent; the whole mass of oxygen in the liquid volume of dampener and the taps is in the liquid state.

Taking into account the accepted assumptions the PSD algebraic and differential equations are derived. The solutions of such equations are the source of the PSD dynamic characteristics. Consider the above dynamic system consisting of the needle 8 with mass m, coupled elastically with the bellows rigidity J, and linear damping D. Considering the condition of gas in the gas volume is changed adiabatically we obtain [4]:

$$C \cdot \frac{dp_g}{dt} = G_{g.in} - G_{g.out}, \qquad (1)$$

where $C = \dfrac{V_g}{k \cdot R \cdot T_g}$ - acoustic capacity; p_g - pressure in the gas volume ; $G_{g.in}$ - gas mass flow at the gas volume inlet; $G_{g.out}$ - gas mass flow at the gas volume outlet; R — gas constant; V_g - gas cavity volume; T_g - gas cavity temperature; k - adiabatic exponent.

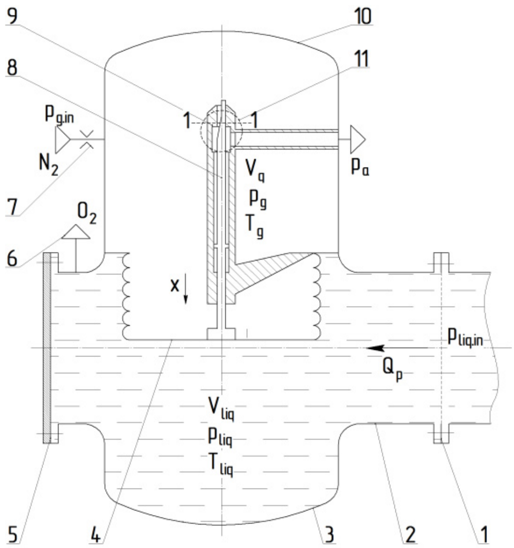

Fig. 1. Air-hydraulic diagram of the PSD:
1 - flange for connection to the fuel line (inlet flange); 2 - inlet pipe; 3 — liquid volume ; 4 - bellows; 5 — filling main line flange (outlet flange); 6 — gaseous medium drainage; 7 — throttle for gas delivery to dampener volume ; 8 - needle; 9 - guide; 10 - gas volume ; 11 - adjustable automatic gas throttle.

Gas flow through the throttling section determined by the needle position is expressed by the Saint-Venant – Wantzel formulas [4]:

$$G_{out} = \mu_{out} \cdot F(x) \cdot p_g \cdot \sqrt{\frac{2}{R \cdot T_g} \cdot \frac{k}{k-1} \cdot \left[\left(\frac{p_a}{p_g} \right)^{\frac{2}{k}} - \left(\frac{p_a}{p_g} \right)^{\frac{k+1}{k}} \right]} \tag{2}$$

for $\frac{p_a}{p_g} > \beta_{cr}$ and

$$G_{out} = \mu_{out} \cdot F(x) \cdot p_g \cdot \sqrt{\frac{k}{R \cdot T_g}} \cdot \left(\frac{2}{k+1} \right)^{\frac{k+1}{2\cdot(k-1)}}, \tag{3}$$

for $\frac{p_a}{p_g} \le \beta_{cr}$,

where μ_{out} - flow coefficient in the gap between the needle and the guide 9; *F(x)* — variable area of the flow section of the adjustable automatic gas throttle; p_a - atmospheric pressure; β_{cr} - critical pressure ratio.

The flow section area *F(x)* is determined in accordance with the dependencies graphically presented in Fig. 2.

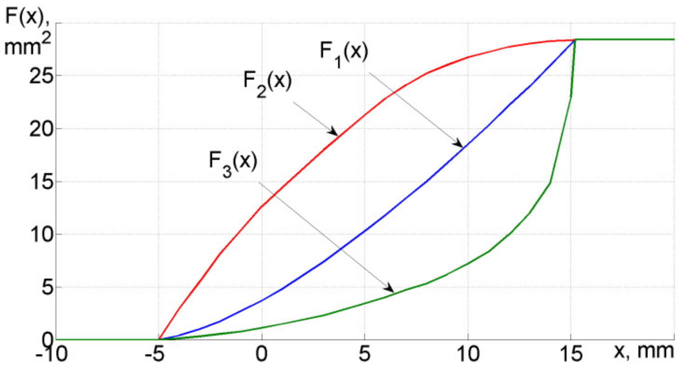

Fig. 2. Dependence of the flow section area of the adjustable automatic gas throttle on the needle position/

Gas mass flow at the gas volume inlet determined by the throttle 7 with supercritical pressure difference is written similarly to the expression (3):

$$G_{in} = \mu_{in} \cdot F_{in} \cdot p_{g.in} \cdot \sqrt{\frac{k}{R \cdot T_g}} \cdot \left(\frac{2}{k+1} \right)^{\frac{k+1}{2\cdot(k-1)}}, \tag{4}$$

where μ_{in} - flow coefficient of the throttle 7; F_{in} - the flow section area of the throttle 7.

Mass gas flow caused by motion of the bellows end surface is defined as follows:

$$G_{g.x} = \frac{p_g}{R \cdot T_g} \cdot \frac{dx}{dt}, \tag{5}$$

where x — motion of the needle; t - time.

The balance equation of the needle as a dynamic element with lumped parameters m, J, D, can be represented as follows:

$$m \cdot \frac{d^2 x}{dt^2} + D \cdot \frac{dx}{dt} + N_{fric} \cdot sign(\frac{dx}{dt}) + J \cdot x + p_{liq} \cdot F_{bel} - p_{\mathrm{g}} \cdot F_{bel} + m \cdot g \cdot (1 \pm n_x) = 0, \tag{6}$$

where m - reduced mass of the needle with the bellows; N_{fric} - dry friction force; p_{liq} - pressure in the liquid volume ; F_{bel} - equivalent area of the bellows end surface; g - acceleration of gravity; n_x - axle overload.

Next, we write basic formulas defining work processes in the liquid volume . Pressure change in the liquid volume is associated with the change of inflowing liquid amount:

$$\frac{V_{\mathrm{liq}}}{\rho_{\mathrm{liq}} \cdot c^2} \cdot \frac{dp_{liq}}{dt} = Q_{\mathrm{liq\,x}} + Q_{\mathrm{p}}, \tag{7}$$

where V_{liq} - liquid volume volume; ρ_{liq} - liquid density; $Q_{\mathrm{liq\,x}}$ - volume liquid flow associated with motion of the bellows end surface; Q_{p} - volume liquid flow through the flange into the inlet pipe 2.

Hydraulic losses could be not taken into account due to their smallness, thus equation of inlet pipe liquid motion turns into the following form:

$$(\mathrm{p}_{\mathrm{liq.in}} - \mathrm{p}_{\mathrm{liq}} - R_{\mathrm{p}} \cdot \rho_{liq} \cdot Q_{\mathrm{p}}) \cdot \frac{\mathrm{F}_{\mathrm{pipe}} \cdot \rho_{\mathrm{liq}}}{l_{\mathrm{pipe}}} = \frac{dQ_{\mathrm{p}}}{\mathrm{dt}}, \tag{8}$$

where $\mathrm{p}_{\mathrm{liq.in}}$ - liquid oxygen pressure after the flange; $\mathrm{p}_{\mathrm{liq}}$ - liquid pressure at the outlet of the pipe (before bellows butt-end); F_{pipe} - the inlet pipe area; $R_{\mathrm{p}} = \dfrac{128 \cdot \nu \cdot l_{\mathrm{pipe}}}{\pi \cdot d_{\mathrm{pipe}}^4}$ - pipe connection resistance for laminar flow mode; ν - fluid oxygen kinematic viscosity; d_{p} - pipe connection diameter. l_{pipe} - length of the pipe; Q_{p} - the inlet pipe volume flow.

Mass gas flow going into the liquid volume pressure change is defined similarly to formula (5):

$$Q_{liq.x} = F_{bel} \cdot \frac{dx}{dt}. \tag{9}$$

3. Analysis of dampener transient characteristics

Obtained system of equations (1) - (9) describes the functioning of the PSD. Analysis of dampener transient characteristics was conducted by numerical method in MATLAB/SIMULINK software package. Quartic and quintic one-sweep explicit Runge-Kutta method (ode 45) was used for simulation. This is a classical method recommended for the first attempt to solve a problem. The method works well in many cases.

Fig. 4-7 show the curves of changes of the needle position, pressure in the liquid and the gas volume s, as well as gas mass flow at the output with respect to time as pressure $\mathrm{p}_{\mathrm{liq.in}}$ of liquid before the inlet flange increases stepwise (Fig. 3).

When modelling transient characteristics the gas mass flow $G_{g.in}$ into a gas chamber remains constant and is determined by the inlet pressure $p_{g.in}$ and the area of the flow orifice 7. At various characteristics of automatically adjustable throttle it's needle position takes the steady-state values x_1, x_2, x_3 (figure 4), while in the gas cavity pressures p_{g1}, p_{g2} and p_{g3} are set, respectively (figure 5). According to the continuity equation for the gas cavity at the steady state the output gas flow rate G_{out} equals to the input flow rate $G_{g.in}$ and at the inlet pressure $p_{g.in} = 5.4\,МПа$ is *11.8* g/s (Fig. 7). Due to the fact that under external force the bellows can be stretched or compressed from it's equilibrium position (*x=0*), the pressure in the gas cavity may be either more or less than the pressure in the liquid cavity (figure 6). According to the selected positive x direction, the bellows is stretched and at its end a balance of power in which the pressure in the gas cavity exceeds the pressure in the fluid cavity. In case of a negative region of *x*, when the bellows is compressed, there is a reverse effect, in which the power from the rigidity of the bellows acts against the pressure forces from the liquid cavity, the pressure in the gas cavity is less than the pressure of the liquid cavity.

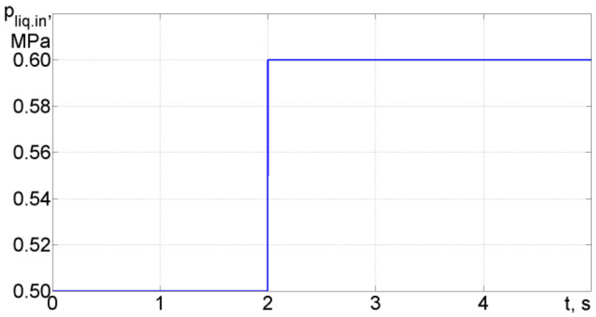

Fig. 3. Disturbing influence in the form of pressure step change at the dampener flange inlet

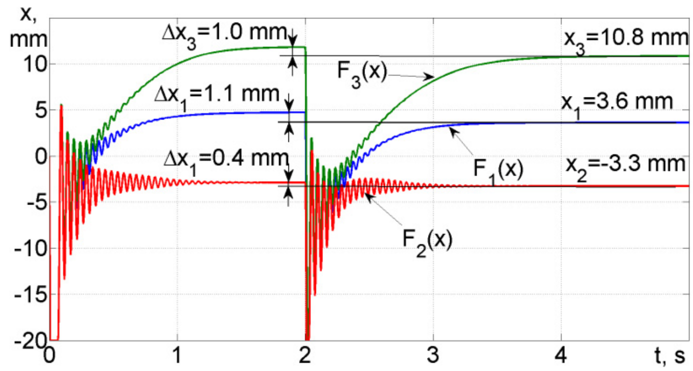

Fig. 4. Transient processes with respect to the needle position upon step change of liquid pressure before the inlet flange for geometric areas variations of the flow area of the automatically regulated gas throttle.

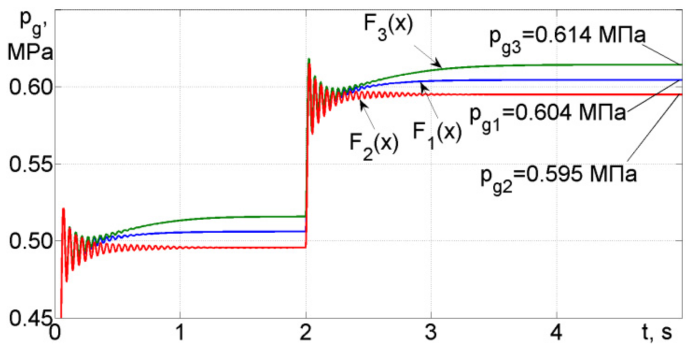

Fig. 5. Transient processes with respect to pressure in the gas volume upon step change of liquid pressure before the inlet flange for geometric areas variations of the flow area of the automatically regulated gas throttle.

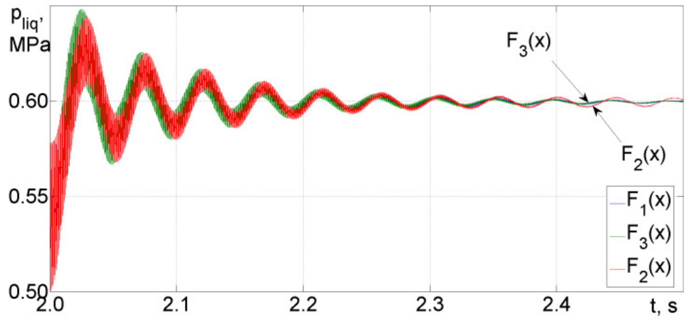

Fig. 6. Transient processes with respect to pressure in the liquid volume upon step change of liquid pressure before the inlet flange for geometric areas variations of the flow area of the automatically regulated gas throttle.

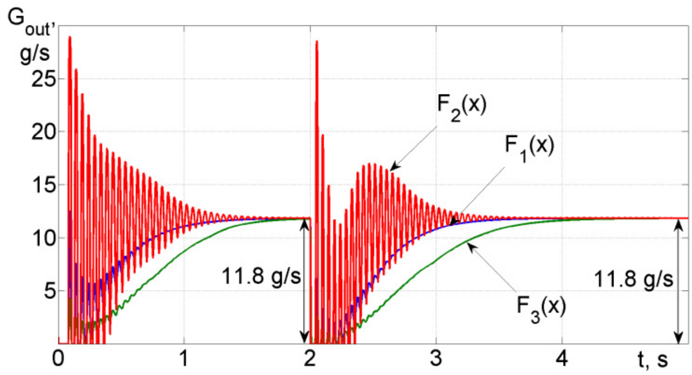

Fig. 7. Transient processes with respect to mass gas flow at the output upon step change of liquid pressure before the inlet flange for geometric areas variations of the flow area of the automatically regulated gas throttle.

The analysis of the above diagrams shows that the dampener optimal functioning will be provided with characteristic $F_1(x)$ close to linear one. The steeper dependence $F_3(x)$ may result in excessive oscillating process of the dampener operational parameters and probably in the latter's failure. On the contrary, the flatter characteristic $F_2(x)$ shows increased dampening because of increase of the gas volume pneumatic rigidity, which results in the PSD speed reduction.

4. Analysis of the gas PSD frequency characteristics

The gas PSD frequency characteristics are needed in analyzing an influence of fuel feed main lines on PP dynamic properties. To determine the frequency characteristics of the gas PSD the AMESim package was used, which due to its practicality can be applied when solving this type of problems.

The gas PSD simulation for producing the frequency characteristics was in accordance with the diagram in Fig. 1 and the formulas (1)…(10). The PSD model made in AMESim software package is shown in Fig. 8.

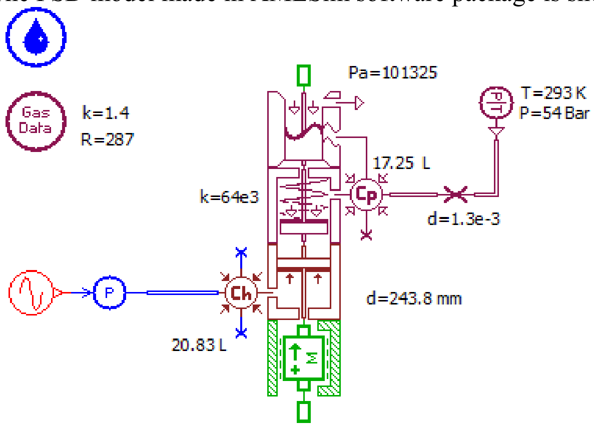

Fig. 8. The gas PSD calculation model made in AMESim software package.

In the damper simulating in AMESim package the following values were taken into consideration: inertia, volume and friction in the inlet main line, volume change of liquid and gas PSD volume s, bellows elastic properties, bellows mass and sliding friction of moving elements [5]-[8]. Dependence of the needle opening area on its shift $F_2(x)$ was assigned in the table form in accordance with the diagrams presented in Fig. 2.

Small deflection linearization of nonlinear functions appeared in the equation system was carried out automatically in calculation of the gas PSD frequency characteristics in AMESim software package. Amplitude-frequency and phase-frequency characteristics of the PSD were calculated as the ratio of complex oscillation amplitude of flow at the PSD input to complex oscillation amplitude of liquid pressure. This ratio of the gas PSD parameters is called acoustic admittance of the PSD.

Fig. 9 presents module and argument of acoustic admittance or amplitude-frequency and phase-frequency characteristics of the PSD.

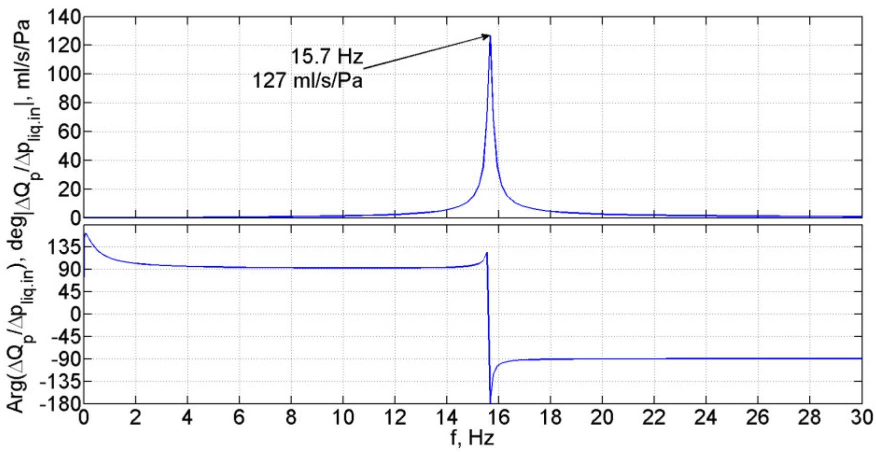

Fig. 9. Amplitude-frequency and phase-frequency characteristics of the gas PSD.

From the analysis of amplitude-frequency characteristics in Fig. 9 it follows there is a great resonance at the oscillation frequency of 15.7 Hz, which will be implemented the flow rate (pressure) damper absorbing vibrations highest efficiency and correction of dynamic characteristics of the fuel line. From the phase-frequency characteristics it is clear that for lower resonant frequencies of the damper has a capacitive feature with a positive phase shift that reduce the resonant frequency of the fuel line, and for the higher resonant frequency of the inertial feature with a negative phase shift. For example, the connection of such a damper to the fuel line booster can shift its resonance frequency to lower frequencies with lower amplitudes.

Thus there is offsetting of the fuel line frequency from the rocket shell resonant frequency that enhances its longitudinal stability.

Represented in Fig. 9 graphs and their computational dependencies are the main characteristic of the damper, which is useful when solving the correction of the dynamic characteristics of the fuel lines.

Figure 10 shows dependency of the volume received in the cavity of the damper fluid from the pressure at its inlet with harmonic oscillations on the subresonance, resonance and after resonance frequencies respectively. From the presented characteristics it is clear that they represent the hysteretic dependence, both for mechanical damper in the form of the load applied to PSD on deformation. The larger the area covered by closed curves, the more fuel pressure oscillation energy absorbed by the damper. From the graph in Fig. 10 follows that at the resonant frequency of this square is the largest, respectively, and will be more process oscillation energy absorbed by the damper. If required process oscillation energy loss is set, it is possible to choose the parameters of the damper for its absorption. The slopes of the hysteresis curves depend on the frequency of flow (pressure) oscillation at the inlet of the damper.

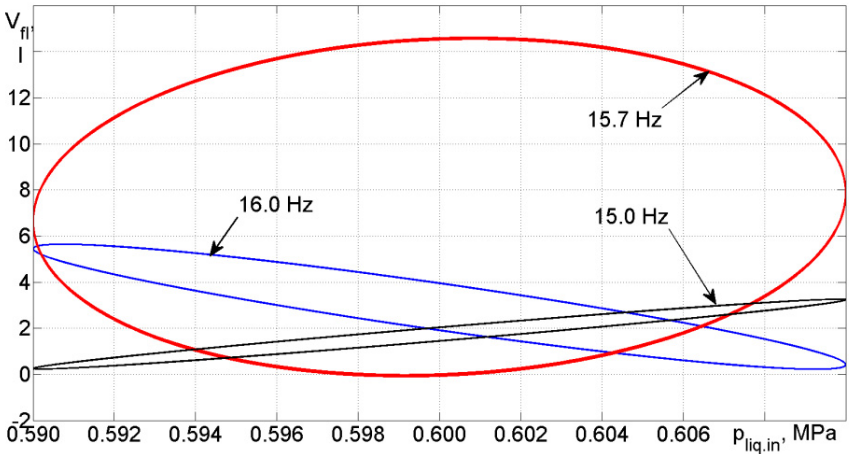

Fig. 10. Dependence of the volume change of liquid coming into the PSD volume on pressure at the pipe inlet at harmonic oscillations on the subresonance (15 Hz), resonance (15.7 Hz) and after resonance (16 Hz) frequencies.

5. Acknowledgement

This work was supported by the Ministry of Education and Science of the Russian Federation

6. Conclusion

The mathematical model and method of calculation of PSD frequency and transient characteristics can be used for correction of dynamic characteristics of the fuel supply lines by tuning frequency offsetting the resonant and pressure fluctuations damping. The graphic dependences fully characterize the properties of the PSD and are sufficient for use in a mathematical model of the corrected fuel line in analyzing its stability and transients. In the future, the authors plan to conduct experimental studies of the PSD on model setup with the task of flow fluctuations at the input to verify adequacy and accuracy of the mathematical model of methods of calculation of transient and frequency characteristics.

The developed mathematical model of the gas PSD may be used while exploring dynamic characteristics of the fuel-supplying main lines, predicting the deviation of its characteristics caused by technological spread of element parameters of the unit or by defect appearing in their construction. Besides, the developed mathematical model of the gas PSD is undoubtedly one of the constituents in modeling the dynamic processes in the fueling system and in estimating the PP stability margin.

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